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Optimization of Parameters in the Production of Turmeric Powder Using a Hammer Mill-Type Pulverizer

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ABSTRACT

The effect of moisture content, rotor blade tip speed and grinding screen perforation diameter on the performance of a hammer mill-type pulverizer was studied. One hundred sixty five kilograms of turmeric rhizomes were washed, sliced, dried to different moisture contents and ground by the pulverizer. The experiment used the Box-Behnken design and the parameters were optimized using the Surface Response Methodology approach.

ANOVA showed that all the control parameters significantly influenced the response variables input grinding capacity, grinding recovery, and overall average particle diameter. Input grinding capacity decreased as moisture increased from 5% to 15%, increased at high RBTS and large SPD. Blade tip speed played a significant role in the efficiency of grinding; recovery was high at high speeds (>35 m s^{-1}). The average particle sizes of the turmeric powder ranged from 0.449 to 1.10 mm. Second-order polynomial models were developed to predict responses for different control variable settings. Optimum machine performance can be obtained at MC of 7.4%, RBTS of 49.1 m s^{-1} and SPD of 1.0 mm. At these settings, predicted values of grinding capacity, grinding recovery, and APD are 142.3 kg h^{-1}, 100% and 0.494 mm, respectively. End-user requirements for fine grinding and good machine performance can be obtained at these settings.

Keywords: hammer mill, optimization, box-behnken, surface response methodology, powder processing, pulverizer, turmeric

Abbreviations: APD – overall average particle diameter; MC – moisture content; RBTS – rotor blade tip speed; SPD – grinding screen perforation diameter

INTRODUCTION

The turmeric plant is a perennial herb cultivated extensively in south and southeast tropical Asia. The most important component of turmeric is curcumin, which makes up 2% to 5% of the rhizome.

As cited by Balakrishnan (2007), several studies have shown that consumption of turmeric reduces blood cholesterol, prevents LDL oxidation, inhibits platelet aggregation, suppresses thrombosis and myocardial infarction, suppresses symptoms associated with type II diabetes, rheumatoid arthritis, multiple sclerosis and Alzheimer's disease, enhances wound healing, protects from liver injury, protects from cataract formation, protects from pulmonary toxicity and fibrosis, and prevention and treatment of a variety of other diseases.

The recent public attention in organic foods and herbal supplements for healthy lifestyles has encouraged the processing of turmeric in powdered form to produce turmeric tea. To make turmeric powder, the rhizomes are washed, sliced, dried and ground to the required particle size.

A package of technology for the processing of powder from turmeric and other root crops was developed by the author. The technology package, which included a root crop slicer, multi-crop cabinet-type dryer, hammer mill-type pulverizer and sieve separator, is currently being used by a project cooperator in Zamboanga del Sur, southern Philippines. The enterprise has created a dependable market for their product such that demand for turmeric powder has increased.

The hammer mill type pulverizer, described in the materials and methods section, is one of the most important machines in the technology package as it directly produces the powder from the dried rhizomes. Most locally-fabricated hammer mills place the hopper discharge directly on top of the rotating blades. This arrangement works well when crushing materials into products of relatively large particle sizes. In the case of powder, however, the fine particles flow back into the hopper opening, scattering the powder outside the machine and contributing to large losses and low grinding recovery. As a remedy, the hopper of the pulverizer was redesigned such that the materials to be pulverized enter the grinding chamber tangentially.

Although the machine performed as per the project cooperator's requirements, there are times, however, when the end-user reported that the product they obtained produced large particle sizes and appeared more like granules than powder. In such cases, the product is re-introduced into the machine for second-pass grinding, consequently reducing the capacity and increasing energy consumption. Investigation showed that this may be due to the grinding of turmeric with incorrect moisture content or operating the machine at unsuitable rotor speed. Sieving of the products showed that the cooperator's requirements are powder of size range 60-40 mesh (250-425 µm). In order to ensure that the quality of the product will pass the end-user's needs, the operating parameters of the pulverizer must be optimized. The end-user will be advised to use the optimized parameters obtained from this study in their future grinding operations.

Optimization is an essential tool in food engineering to achieve efficient operation of processing systems or unit processes. The most frequently used statistical procedure in optimization studies is the response surface methodology. This is a collection of mathematical and statistical method used in the development of relationship between a response of interest, y, and associated control variables denoted by $x1$, $x2, \ldots, xk$ (Madamba, 2002; Bradley, 2007; Khuri and Mukhopadhyay, 2010). In this method, several factors are simultaneously varied, which consequently, reduces the number of experiments, improves statistical interpretation possibilities, and evaluates the relative significance of several factors even in the presence of complex interactions (Sridevi and Genitha, 2012). This approach enables an experimenter to make efficient exploration of a process or system (Madamba, 2002).

The relationship between the response and control variables can be approximated by a second order polynomial model:

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum\sum_{i<j} \beta_{ij}\, x_i x_j + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \epsilon$$

Equation 1

where, βi is the linear main effects, βii are the quadratic main effects, βij are the linear-by-linear interactions (Aslan and Cebeci, 2007; Krishnaa et al., 2013).

The general objective of this study was to determine the effect of selected crop and machine parameters on the performance of a hammer mill-type pulverizer in the grinding of dried turmeric rhizomes into powder. Specifically, it aimed to: (a) determine the optimum combination of the control variables that will produce the required turmeric powder particle size and maximize the performance of the pulverizer, (b) develop a model that will predict the response for given settings of the control parameters.

REVIEW OF LITERATURE

Turmeric (*Curcuma longa*) is a rhizomatous herbaceous perennial plant belonging to the ginger family. It is harvested for its rhizome which has a brown skin and bright orange flesh. The rhizome consists of a central bulb with a number of finger-like lateral offshoots, about 50 to 75 mm long, which break off easily from the bulb.

The rhizomes contain carbohydrates (60-70%), protein (6-8%), fat (5-10%), fiber (2-7%), minerals (3-7%), oil (3-7%), curcuminoids (2-6%) and moisture (6-13%). The curcuminoids are responsible for its bright orange color, while the essential oil is responsible for the distinct turmeric aroma (Balakrishnan, 2007). Turmeric is use as dye, condiment, as principal ingredient in Indian culinary and as a flavoring agent (Shri, 2014). The turmeric content in curry powder blends ranges from 10% to 30% (Plotto, 2004).

There are several methods of processing turmeric rhizomes into powder. The most common procedure employs the following steps: (a) curing, (b) slicing, (c) drying, and (d) grinding. Curing involves boiling the rhizomes in water for 45 minutes to one hour in order to gelatinize the starch for more uniform drying, improve color and remove odor (Plotto, 2004). The cured rhizomes are then sliced and dried, either by sun-drying or through the use of mechanical dryers, to a moisture level of 5% to 20%, with drying temperature preferably controlled at 60°C. The rhizomes are then ground and crushed into small particles and sifted through a sieve. Large particle sizes further undergo size reduction.

The project cooperator in Zamboanga del Sur has adopted the following processing steps: (a) washing, (b) slicing, (c) drying, (d) grinding and (e) sieve sifting. The author have designed and fabricated the equipment required for each of these steps.

The size of grind varies considerably and may depend on end use or intended market. According to Sridhar (2005) for use as spice, turmeric is milled to fine powder of size 200–500 microns. In India, where turmeric is prime export commodity, Agmark specifies turmeric powder as standard or coarse grind depending whether all powder passes a 300- or a 500-micron sieve, respectively (http://epgp.inflibnet.ac.in). Fellows and Axtell (2014) recommend milling turmeric to 300-microns, while Plotto (2004) reported that the rhizomes are usually ground to approximately 60-80 mesh (250–180 µm) particles when blended with other ingredients to make curry powder. In the Philippines, no current efforts have been made to standardize turmeric powder particle size. Sizes of grind usually depend on the processor. For this study, particle sizes of turmeric powder were designed to meet the requirements of the project cooperator. Personal interview with the cooperator and by direct sieving of samples showed that the cooperator requires powder of size range 60-40 mesh (250-425 microns).

Raw materials often occur in sizes that are too large for its intended use and, therefore, must be reduced in size. Size reduction includes the mechanical processes of cutting, shearing, crushing, grinding, and milling grains and other food materials (Rudnitski, 1990).

In the grinding process, materials are reduced in size by fracturing them, applying stress through the action of mechanical moving parts. Initially, the stress is absorbed internally by the material; when the local strain energy exceeds a critical level, fracture occurs along fault lines and the stored energy is released (Bhatt and Agrawal, 2007). Part of the energy is used in the creation of new surfaces, but the greater part is dissipated as heat.

The force applied to grind materials may be compression, impact, cutting, shear, or a combination of these forces (Pallman, undated). Grinding mills using impact as mechanism for size reduction generally have higher peripheral speeds compared to other types of grinding machines. The optimum size of the grind depends on the intended use of the material. Accordingly the conventional methods of grinding normally employ a hammer mill, roller mill, pinmills used in food processing usually produces particles with sizes which may vary from 850 mm – 50 µm (Sridhar, 2005).

Factors affecting the quality of the final product undergoing size reduction process can be classified as those belonging to the material and those that are due to the grinding machine. Properties of the material that affect size reduction are the following (Bhatt and Agrawal, 2007; Sushant and Archana, 2013): (a) hardness, (b) toughness, (c) abrasiveness, (d) stickiness, (e) temperature, (f) material structure, and (g) moisture content.

Either fixed or swinging hammer blades are attached to a rotor that rotates at high speed inside the casing of a hammer mill. The material is crushed and pulverized between the hammers and the casing and remains in the mill until it is fine enough to pass through a screen which forms the bottom of the casing. Reduction in a hammer mill is primarily the result of impact between the rapidly moving hammer and the relatively slow moving material. There is some attrition between the particles and between the hammers and the screen.

The following hammer mill parameters influenced to significant extent the efficiency of grinding and the quality of ground products (Rudnitski, 1990; Hoque et al, 2007; Heimann, 2008): (a) hammer tip speed, distribution pattern, number and position, (b) screen area per horsepower, size of perforations, amount of open area, and arrangement of holes, (c) material feeding method, (d) and presence of air assist system. While the basic operational concepts are the same for all hammer mills, the actual operating conditions vary depending on the materials being processed (Heimann, 2008). Grains such as corn, wheat, and sorghum and soft stocks such as soybean meal tend to be friable and easy to grind. Fibrous, oily, or high moisture products are very tough and require much more energy to reduce. Consequently, the hammer mill setup that works well for one will not necessarily work for the other.

Sieve analysis is usually used to determine particle size distribution of ground product. In agricultural process engineering, it is used to gage the performance of size reduction machinery by determining the shape and size of the product before and after reduction, and the range in size and shape of the resultant product (Henderson and Perry, 1982). The procedure is carried out through the use of standard sieves with screen openings ranging from 125 mm to 20 microns.

Pfost and Headley (1976) applied techniques previously used in classifying minerals in the mining and glass manufacturing industries to describe the particle size distribution of certain ground feedstuffs. Their study showed that hammer milled corn and grain sorghum possessed non-normal particle size distributions. The logarithm of the particle size, however, closely resembled normal distribution. The information obtained from the log-normal particle size distribution analysis accurately described the physical characteristics of ground materials.

Baker and Herrman (2002) outlined the steps for particle size analysis based on the method developed by Pfost and Headley (1976). After the ground materials are classified using a stack of US Standard Test Sieves, the parameters are computed based on the following equations:

$$d_i = [(d_u)(d_o)]^{0.5}$$

Equation 2

(a) The particle size of materials retained on a sieve is the geometric mean of the perforation diameters of two adjacent sieves on the stack (Baker and Herrman, 2002):

where,

d_i = particle diameter retained on the *ith* sieve in the stack, μm
d_u = diameter opening through which particles will pass (sieve preceding the *ith* sieve), μm
d_o = diameter opening through which particles will not pass (*ith* sieve), μm

(b) Because it is not practical to count each particle individually and calculate an average, the average particle size, d_{gw}, can be calculated on a weight basis.

(c) The standard deviation, s_{gw}, is:

$$d_{gw} = log^{-1}\left[\frac{\sum(W_i log d_i)}{\sum W_i}\right]$$

Equation 3

$$s_{gw} = log^{-1}\left[\frac{\sum W_i\left(\log d_i - log d_{gw}\right)^2}{\sum W_i}\right]^{0.5}$$

Equation 4

(d) By multiplying and dividing the average particle size, d_{gw}, with the standard deviation, s_{gw}, the upper and lower limit of the range into which 68% of particle sizes will belong can be calculated.

A measure of size distribution can be obtained using the Gates-Gaudin-Schumann plot, which is a graph of cumulative percent passing against sieve size with both axes in logarithmic scales (http://www.chem.mtu. edu). The data plots in a straight line except for the two or three coarsest size measured. The equation of the straight portion of the graph is:

$$y = 100\left(\frac{x}{K}\right)^a$$

Equation 5

Taking the logarithm of both sides,

$$\log y = a \log x + (2 - a \log K)$$

Equation 6

which is an equation of straight line with slope = a and y-intercept = 2-a log K.

The size modulus, K, is a measure of how coarse the size distribution is, while the distribution modulus, a, is a measure of how broad the distribution is (http://www.chem.mtu.edu).

MATERIALS AND METHODS

Description and Principles of Operation of the Machine

The pulverizer used in the study was a swinging-type hammer mill consisting of a rotor which has two plates fixed to the main shaft and enclosed in the grinding chamber. The rotor plates held four sets of rotor pins with four hammer blades in each pin. The blades pivot on the pin and can swing freely. A semi-circular removable perforated steel screen is located on the bottom part of the grinding chamber. A 3-hp electric motor drives the hammer mill. Except for the holding frame, all materials are made of stainless steel (Figure 1).

Dried food materials enter the mill tangentially through an opening on the grinding chamber. The materials are then impacted by rotating blades until the particles are sufficiently reduced to sizes smaller

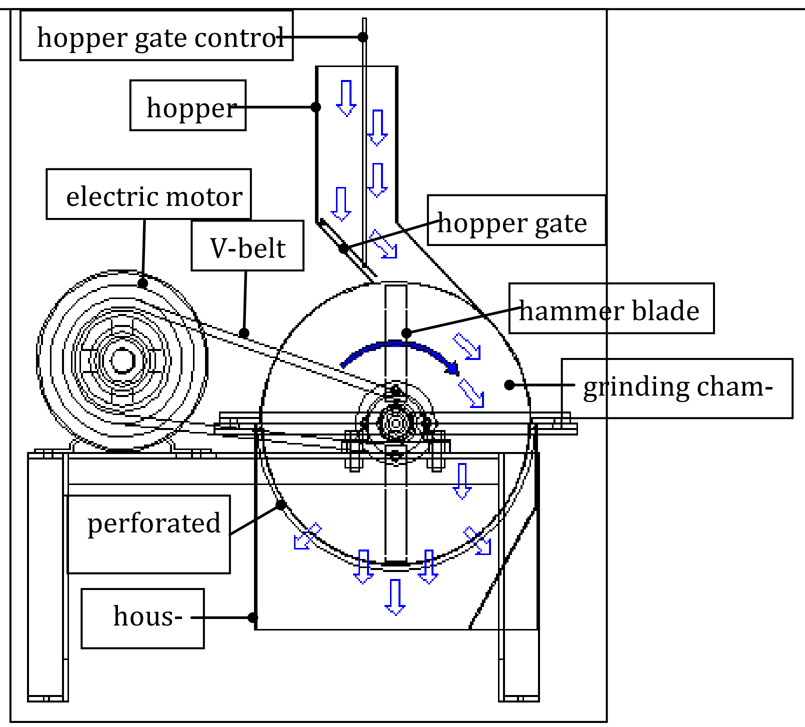

Figure 1. Basic parts of the hammer-mill type pulverizer. Outline arrows show the path of the turmeric rhizome as it undergoes pulverization; solid arrow show the rotation of hammer blades.

than the screen perforation diameter. Ground materials pass through the perforated screen and are collected by a pan placed below the outlet of the grinding chamber.

Experimental Design

A fractional three-level three factor incomplete factorial Box-Behnken experimental design was used in the optimization study. The Box-Behnken design is a method for developing second-order response surface models, and is based on the construction of balanced incomplete block designs which requires at least three levels for each factor (Tekindal, et al. 2012). The design substantially reduces the number of experimental runs without decreasing the accuracy of the optimization process (Qiu et al., 2014). The sample size is kept to a value which is sufficient for the estimation of the coefficients of the polynomial model (Cavazzuti, 2013).

The control parameters included moisture content of the dried turmeric slices (*X1*), rotor blade tip speed (*X2*), and screen perforation diameter (*X3*). The range of each of the independent variables was for, *X1*: 5 – 15% (w.b)., *X2*: 10 – 60 m s^{-1} corresponding to rotor speeds of approximately 579 to 3472 rpm, and *X3*: 1 – 5 mm.

Response Variables

Surface response models were developed in order to determine the effect of the parameters on the following response variables:

$$Y1\!:Input\ Grinding\ Capacity, kg\ h^{-1} = \frac{samples\ collected\ in\ 20s\ run, g}{20\ s}\frac{3600}{1000}$$

$$Y2\!:Grinding\ recovery, \% = 100\frac{total\ weight\ of\ ground\ samples, g}{1000\ g}$$

Y3: Overall Average Particle Diameter, mm

The overall average particle diameter was obtained using the method of Baker and Hermann (2002).

Sample Preparation

One hundred sixty five (165) kilograms of turmeric rhizomes were purchased from a farm in the project site. The rhizomes were washed manually in running water and cleaned with the use of a plastic brush. After thorough washing, the rhizomes were cut into approximately 3-mm thick slices using a mechanical slicer (BIOMECH slicer, UPLB). The sliced rhizomes were spread uniformly on the drying tray at two-layer thickness and placed into a cabinet dryer (BIOMECH multi-crop cabinet-type dryer, UPLB).

The average initial moisture content of fresh turmeric was 84.4% (w.b.) determined by drying three 25-g samples taken randomly from the sliced rhizomes in an infrared electronic moisture analyzer (Scaltec SMO-01, Scaltec Instruments GmbH, Germany). Moisture content wet-basis was computed.

Drying and Pulverization of Sliced Turmeric

Fifteen (15) lots of sliced turmeric rhizomes were dried separately at 60ºC using the BIOMECH cabinet-type dryer. The samples were dried continuously until the required moisture contents of 5%, 10% and 15% wet basis were attained.

The dried turmeric rhizomes were packed and sealed in plastic bags and temporarily stored at ambient conditions while waiting for further analyses. Pulverization of the samples was performed using the hammer mill-type pulverizer according to the requirements of the Box Behnken experimental design. One kilogram of dried turmeric rhizomes was used in each run. Powdered turmeric was collected at the outlet chute of the pulverizer. After each run, the grinding chamber of the machine was opened and the un-pulverized turmeric was also collected. The collected powder samples were weighed and sealed in plastic bags for sieve analysis.

Particle Size Analysis

Sieve analysis of turmeric powder sample was carried out using a sieve shaker (Ro-Tap Model B, Humboldt Manufacturing Company, USA) following the standard procedures outlined by the American Society for Testing Materials (ASTM) C136-01. ASTM Standard Test Sieves with mesh sizes of 16, 20, 30, 40, 50, 70 and 100 were stacked in ascending order to obtain particle sizes of 1180, 850, 600, 425, 300, 212 and 150 µm, respectively. Particle size analysis was performed following the procedure proposed by Baker and Herrman (2002) as adapted from the methods developed by Pfost and Headley (1976).

Table 1. The Box-Behnken experimental design matrix and data for each response variables.

	CONTROL VARIABLES						RESPONSE VARIABLES		
	Coded Values			Actual Values					
Run	*X1*	*X2*	*X3*	*X1*	*X2*	*X3*	*Y1*	*Y2*	*Y3*
1	-1	-1	0	5	10	3	50.3	0.63	0.9225
2	+1	-1	0	15	10	3	17.4	0.41	1.0558
3	-1	+1	0	5	60	3	139.7	0.99	0.7858
4	+1	+1	0	15	60	3	119.4	0.98	0.8778
5	-1	0	-1	5	35	1	155.0	0.98	0.5282
6	+1	0	-1	15	35	1	103.4	0.85	0.5387
7	-1	0	+1	5	35	5	162.8	0.98	0.9476
8	+1	0	+1	15	35	5	155.2	0.98	1.0816
9	0	-1	-1	10	10	1	12.1	0.38	0.5901
10	0	+1	-1	10	60	1	100.3	0.97	0.4493
11	0	-1	+1	10	10	5	82.2	0.62	1.0966
12	0	+1	+1	10	60	5	117.8	0.98	0.9173
13	0	0	0	10	35	3	117.5	0.99	0.8409
14	0	0	0	10	35	3	131.3	0.98	0.8131
15	0	0	0	10	35	3	135.2	0.98	0.8644

Control Variables: *X1* = Moisture Content, %wb; *X2* = Rotor Blade Tip Speed, m s^{-1}; *X3* = Screen Perforation Diameter
Response Variables: *Y1* = Input Grinding Capacity, kg h^{-1}; *Y2* = Grinding Recovery; *Y3* = Overall Average Particle Diameter, mm

RESULTS AND DISCUSSION

Table 1 shows the Box-Behnken experimental design matrix and the corresponding data for each run. Table 2 shows the summary of the results of the analysis of variance for the data shown in Table 1.

Effect on grinding capacity

Table 1 shows that input grinding capacity ranged from a low of 12.1 kg h^{-1} for Run 9 (X1 = 10%, X2 = 10 m s^{-1}, X3 = 1 mm) to a high of 162.8 kg h^{-1} for Run 7 (X1 = 5%, X2 = 35 m s^{-1}, X3 = 5 mm).

Input grinding capacity was significantly affected by moisture content, rotor blade tip speed and screen perforation diameter (Table 2). The interaction between the main parameters did not significantly influence grinding capacity. Except for blade tip speed, the quadratic terms also did not significantly affect the response variable.

Contour plots show that at any blade tip speed and screen perforation diameter, grinding capacity decreases as moisture content increases from 5% to 15%, wb (Figure 2). Visual observation showed that at 5% MC, the dried sliced rhizomes were more friable and brittle than the rhizomes at 15% (Figure 3). This change in the physical characteristic of the material may have contributed to the ease in which grinding was performed. Friable materials tend to be more susceptible to crumble (Sushant and Archana, 2013; Rudnitski, 1990) and break along well-defined planes (Swain, et al. 2011).

As reported by Sushant and Archana (2013) the presence of more than 5% moisture influenced the hardness, toughness, stickiness of substance, and that, in general, materials with MC below 5% are more suitable for dry grinding. These findings were also corroborated by Yancey et al. (2009) who reported the same trend in the grinding of switchgrass and corn stover.

El Shal, et al. (2010) showed that machine capacity in the hammer milling of corn increased with increase in drum speed from 23 m s^{-1} to 33 m s^{-1} and decrease in moisture content from 14% to 12% wb.

Input grinding capacity also in-creases as the screen perforation diameter increases; although the actual capacity tends to be much lower at blade tip speed of 10 m s^{-1} compared to that of higher tip speeds. Ground material passes more easily through the grinding screen of larger perforation diameters. At speed of 10 m s^{-1}, impact energy is not sufficiently large to break the materials into fine particles, thus lowering the capacity and producing output with large particle size. However, at any settings of moisture content and screen perforation diameter, higher capacity can be obtained at blade tip speed of 35 m s^{-1} compared to that at speed of 60 m s^{-1}. At higher blade speed, the particles tend to rotate along and at the same speed as the

Table 2. Analysis of variance table showing the significance of the effect of the control parameters on the response variables.

Source	*Y1*	*Y2*	*Y3*
Model	30649.86 **	0.6844 **	0.5962 **
X1: Moisture Content	1579.22 *	0.0162 **	0.0171 **
X2: Rotor Blade Tip Speed	12418.88 **	0.4418 **	0.0504 **
X3: Screen Perforation Diameter	2708.48 *	0.0181 **	0.4689 **
X1 · X2	39.69 ns	0.0110 **	0.0004 ns
X1 · X3	484.0 ns	0.0042 *	0.0038 *
X2 · X3	691.69 ns	0.0132 **	0.0004 ns
X1 · X1	358.24 ns	0.0004 ns	0.0062 *
X2 · X2	11641.19 **	0.1794 **	0.0034 *
X3 · X3	144.23 ns	0.0024 ns	0.0417 **
Residual	846.70	0.0032	0.0022
Lack of Fit	673.72 ns	0.0031 *	0.0008 ns
Pure Error	172.98	0.0001	0.0013
Standard Deviation	13.01	0.025	0.021
Mean	106.64	0.847	0.821
Coefficient of Variance, %	12.20	2.97	2.53
R-squared	0.9731	0.9954	0.9963
Adjusted R-squared	0.9247	0.9871	0.990

* significant at 5%; ** significant at 1%; ns not significant
Y1 = Input Grinding Capacity; *Y2* = Grinding Recovery; *Y3* = Overall Average Particle Diameter

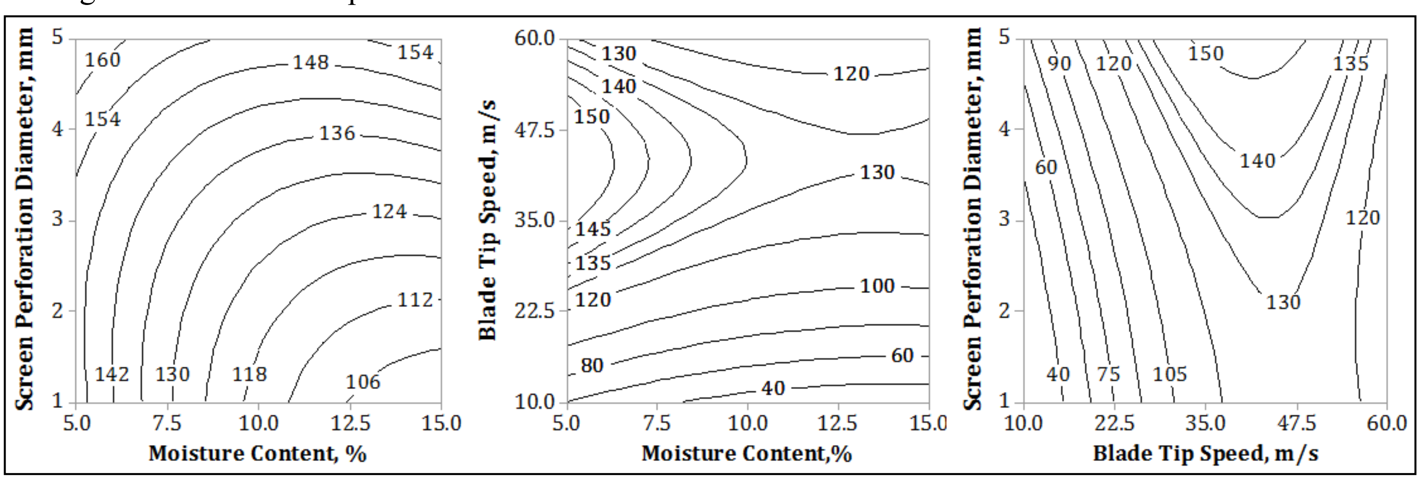

Figure 2. Contour plots of input grinding capacity

rotating blades inside the grinding chamber, thus preventing the transfer of energy from the blades to the materials, and consequently also preventing impact and size reduction to take place.

Effect on grinding recovery

Table 1 shows that grinding recovery ranged from 38% to 99% depending on the settings of the control parameters. ANOVA shows that all the main parameters significantly affected grinding recovery, at 99% confidence level (Table 2). The interactions of the main parameters, as well as the squared term of blade tip speed, also had significant effect on grinding recovery.

The efficiency of grinding was reduced when moisture content of the turmeric rhizome was high as shown by the decrease in grinding recovery when moisture was increased from 5% to 15% (wb) at any setting of blade tip speed and screen perforation diameter (Figure 3). This result is supported by a study of Probst, et al. (2013) which showed that at a moisture level of 20%, un-ground materials left in the grinding chamber of the hammer mill was more than 70% of the initial mass. Yancey et al. (2009) also noted that efficiency of grinding switchgrass and corn stover was reduced by 40% to 50% as the moisture content in the biomass increased from 10% to 25% (wb).

The surface contour graphs of Figure 3 also revealed that blade tip speed plays a very significant role in the grinding of turmeric. Grinding recovery is high at high blade tip speed (>35 m s^{-1}) at all settings of moisture content and screen perforation diameter. This finding is consistent with the findings of Heimann (2008) that hammer mills with high tip speed will always grind finer, thus making it easy for the powder to pass through the screen perforations leaving nothing or only a small amount of unground materials on the grinding screen. At lower tip speeds (10 m s^{-1}), grinding recovery is low, and barely exceeded 50%, especially when screen perforation diameter is small and moisture content of the turmeric is high.

Fig 3. Dried turmeric rhizomes with moisture content of 15% w.b. (a) and 5% w.b. (b).

Particle Size Analysis

Table 3 shows a summary of the different particle size characteristics of the powdered turmeric rhizomes. The fineness modulus, FM, varied from 3.65 to 6.19 with a mean of 5.28±0.80 indicat-

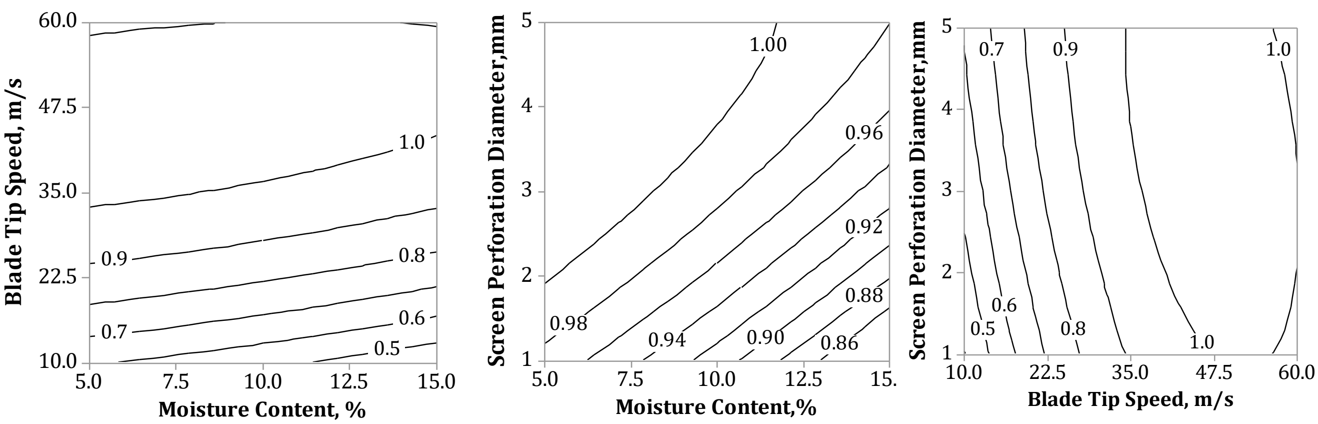

Fig 4. Contour plots of grinding recovery.

Table 3. Summary of the particle size analysis of the turmeric powder subjected to different settings of the control parameters.

PARAMETER	BOX-BEHNKEN TEST RUNS				
	Run 1	Run 2	Run 3	Run 4	Run 5
Fineness modulus (FM)	5.62	6.13	5.27	5.60	4.13
Size modulus (K)	68.83	184.68	209.50	246.61	240.47
Overall average diameter (d_{gw}, µm)	922.55	1055.76	785.76	877.79	528.20
Standard deviation (s_{gw})	1.79	1.70	1.72	1.71	1.51
PARAMETER	**Run 6**	**Run 7**	**Run 8**	**Run 9**	**Run 10**
Fineness modulus (FM)	4.19	5.82	6.19	4.43	3.65
Size modulus (K)	238.59	228.52	150.29	146.78	190.25
Overall average diameter (d_{gw}, µm)	538.67	947.65	1081.59	590.08	449.33
Standard deviation (s_{gw})	1.58	1.70	1.67	1.66	1.50
PARAMETER	**Run 11**	**Run 12**	**Run 13**	**Run 14**	**Run 15**
Fineness modulus (FM)	6.12	5.60	5.46	5.38	5.55
Size modulus (K)	79.92	77.18	163.11	252.15	233.59
Overall average diameter (d_{gw}, µm)	1096.62	917.27	840.86	813.09	864.44
Standard deviation (s_{gw})	1.62	1.74	1.79	1.74	1.69

ing that the particle sizes were medium fine to coarse. The size modulus, *K*, also confirmed this with *K*-values ranging from 68.83 to 252.15 with a mean of 180.70±64.46. The particle overall average diameter of the samples ranged from 0.45 mm to 1.10 mm depending on the setting of the control variables during grinding.

ANOVA showed that all the main parameters moisture content, rotor blade tip speed, and screen perforation diameter, and the squared terms significantly affected average particle size of the ground turmeric (Table 2). Except for the interaction between moisture content and screen perforation diameter, all other interactions did not significantly influence the particle sizes of turmeric powder.

At any level of moisture, the ground turmeric particle sizes decreased as blade tip speed increases, and increased with increase in the screen perforation diameter (Figure 5). The particle sizes, however, are relatively finer at screen perforation of 1 mm and as the blade tip speed approaches 60 m s^{-1}. Since the technology user requires turmeric with fine parti-

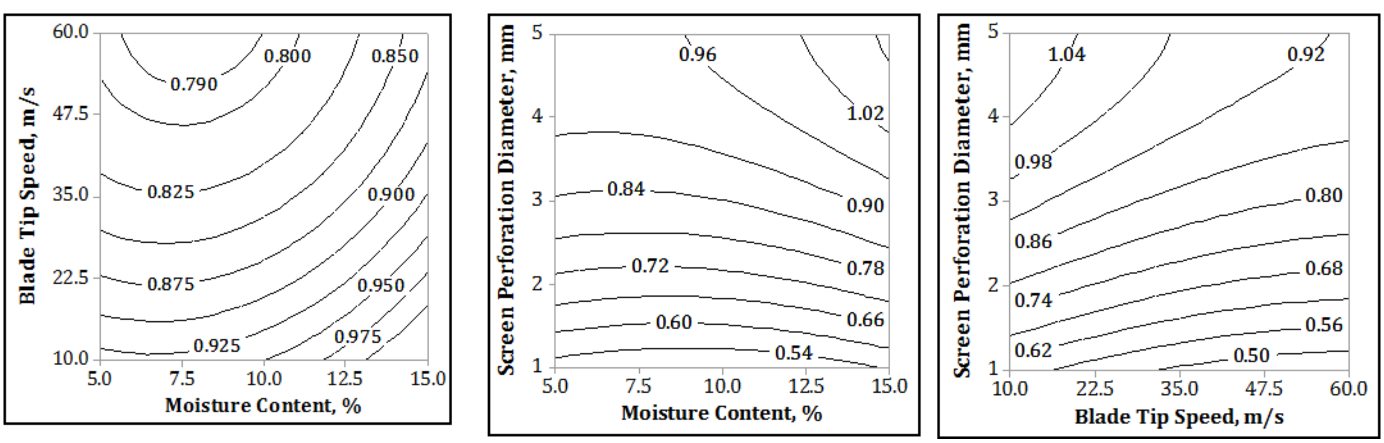

Figure 5. Contour plots for overall average particle diameter of turmeric powder.

cles, then the pulverizer should be operated near or at these settings to obtain the desired product.

Surface Response Models

Analysis showed that the quadratic model was statistically significant and best represented the relationship between the response variables and the associated control variables. The second order polynomial models that accurately fit the data for the response variables were:

$$Y_1 = 30.953 - 14.872X_1 + 8.402X_2 - 1.970X_3 - 0.090(X_2)^2$$

$$Y_2 = 0.2660 - 0.2512X_1 + 0.0333X_2 + 0.0696X_3 + 0.0004X_1X_2 + 0.0032X_1X_3 - 0.0011X_2X_3 - 0.0003(X_2)^2$$

$$Y_3 = 0.522 - 0.02980X_1 - 0.00515X_2 + 0.2564X_3 + 0.0031X_1X_3 + 0.00163(X_1)^2 + 0.0000482(X_2)^2 - 0.02657(X_3)^2$$

Optimization of Parameters and Validation of Model

Table 4 shows the result of the optimization process, the predicted values and the mean of the results of the validation test. With a desirability of 0.852, a maximum input grinding capacity of 142.28 kg/h, maximum grinding recovery of 100.0%, and minimum overall average particle diameter of 0.494 mm will be obtained when moisture content, rotor blade tip speed and screen perforation diameter are 7.4%, 49.0 m/s and 1.0 mm, respectively. Since the value is close to 1.0, the combined desirability of 0.852 shows that the settings of the control parameters will achieve the goals of the optimization (http://support.minitab.com).

Model validation test showed that mean of the input grinding capacity was 147.9 kg/h, about 4.0% higher than the value predicted by the second-order polynomial model. Grinding recovery was 98.9%, about 1.1% lower than the predicted value of 100.0%. The overall average particle diameter was 0.407 mm, relatively lower than the particle size of 0.494 mm predicted by the model. Further studies should be done to determine if these differences are statistically significant.

Post-prediction analysis was done to confirm if the values obtained during the validation runs were valid and fit the second-order polynomial models. All the mean of the experimental values of the response variables obtained during the validation run fell within the lower and upper limits of the prediction interval (Table 5), showing that the results of the validation run were valid and fitted the models.

SUMMARY AND CONCLUSION

Optimization showed that end user requirements of fine grinding and good machine performance can be obtained at the optimum values of the control parameters. Maximum input grinding capacity, maximum grinding recovery and minimum average particle size of the turmeric powder will be obtained when the moisture content of dried sliced turmeric is 5% to 7% (w.b.), the rotor blade tip speed of the

Table 4. Optimum values of the independent variables

OPTIMUM VALUES OF THE CONTROL PARAMETERS	
X1: Moisture content, %	7.4
X2: Blade tip speed, m s^{-1}	49.0
X3: Screen perforation diameter, mm	1.0
Desirability	0.852

Table 5. Optimum values of the predicted values of the response variables and the results of the validation test.

Response Variables	MEAN Predicted	MEAN Actual	% Relative Difference	Standard Deviation Predicted	Standard Deviation Actual	95 % P. I. Low	95 % P. I. high
Y1	142.3	147.9	-3.97	13.01	0.94	111.49	173.08
Y2	100.0	98.9	1.08	0.03	0.81	96.8	108.7
Y3	0.494	0.407	17.70	0.021	0.0011	0.405	0.552

Y1 = input grinding capacity, kg h-1; Y2 = grinding recovery, %; Y3=overall average diameter, mm; P. I. = prediction interval pulverizer is 49 m s^{-1} and the grinding screen mounted on the machine has perforation diameter of 1.0 mm or smaller. By adopting the optimized values of the control parameters, the end-user can expect to obtain turmeric powder with particle sizes less than 500 microns using a machine which will yield a high input grinding capacity of about 150 kg/h and powder recovery close to 100%.

RECOMMENDATIONS

This study was done to investigate the size reduction component of the technology package for turmeric powder processing developed specifically for the project cooperator. Having optimized the parameters for the grinding process, similar studies should be done for the other components of the package to further improve the efficiency of the powder processing system adapted by the project cooperator.

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